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Hard X-ray sky survey with the SIGMA telescope aboard GRANAT observatory

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During the lifetime of GRANAT orbital observatory the SIGMA telescope collected X-ray images of more than 1/4 of the whole sky. Among these regions the Galactic Center had largest exposure time (~9 million sec). In the present work we review all observations of the SIGMA telescope and present sensitivities achieved with it at different sky regions

INTRODUCTION

SIGMA telescope aboard GRANAT observatory was the first space telescope that used coded aperture technique for reconstruction of sky images in hard X-rays (energy band 35-1300 keV). Large lifetime of the telescope (it worked with some interruptions practically 8 years) allowed us to obtain unique set of hard X-ray images of the sky with unprecedented angular resolution ($\sim 15'$) and accuracy of a source localization ($\sim 2-3'$).

Because of these advantages, in particular, telescope SIGMA discovered very interesting hard X-ray source GRS 1758-258, which is located only $40'$ apart from bright soft X-ray source GX 5-1 (Mandrou et al. 1991, Sunyaev et al. 1991). Large variations of hard X-ray flux (>400 keV) was detected in the spectrum of black hole candidate 1E1740.7-2942 (Bouchet et al. 1991, Sunyaev et al. 1991b). There was detected hard X-ray flux from X-ray burster A1742-294, which is very near to bright black hole binary 1E1740.7-2942 (Churazov et al. 1995). There was put an upper limit on hard X-ray flux of central supermassive black hole of our Galaxy (Sunyaev et al. 1991, Goldwurm et al. 1994)

In coming years one can expect a great step in the surveys of hard X-ray sky (20-200 keV). In particular, new hard X-ray observatory INTEGRAL (see Winkler et al.2003) was launched in 2002. It demonstrated the ability to provide 5-8 time better sensitivity than it was available for the SIGMA (see e.g. Revnivtsev et al. 2004). Another observatory with hard X-ray coded mask telescope – SWIFT (see e.g. Gehrels 2000) – is planned for the launch in 2004. In addition to coded mask telescopes the reflection telescopes that can work in the energy band 20-70 keV is being developed (e.g. SIMBOL-X, Fernando et al. 2002). In the view of these advances we decided to publish the overview of survey of hard X-ray sky of the the SIGMA telescope of GRANAT observatory.

During the period 1990-1998 the SIGMA observed more that one quarter of the sky with sensitivity better than 100 mCrab. Galactic Center region had the deepest exposure time (~9 million sec), providing the sensitivity to a source discovery (5σ) approximately 10 mCrab. In the present work we review observations of the telescope, achieved sensitivities and the list of sources that were detected during the period 1990-1998.

RESULTS

Joint French-Soviet hard X-ray telescope SIGMA was one of the main instruments aboard GRANAT orbital observatory. Coded aperture – tungsten mask placed at 2.5m of the positional sensitive NaI detector – allowed to reconstruct images of hard X-ray sky in the energy band 35-1300 keV with angular resolution $\sim 15'$. Thanks to high apogee orbit of GRANAT (period of revolution ~3 days, hight of apogee ~200 000 km) instruments of the observatory could have almost continuous observations during 3 days, with short interruptions for the telemetry dumps. Detailed description of the SIGMA telescope can be found in Paul et al. (1991). In flight performance of the telescope - in work of Mandrou et al. (1991)

During the period 1990-1998 the SIGMA performed more than 500 pointed observations of different astrophysical objects with typical exposure times around 20-24

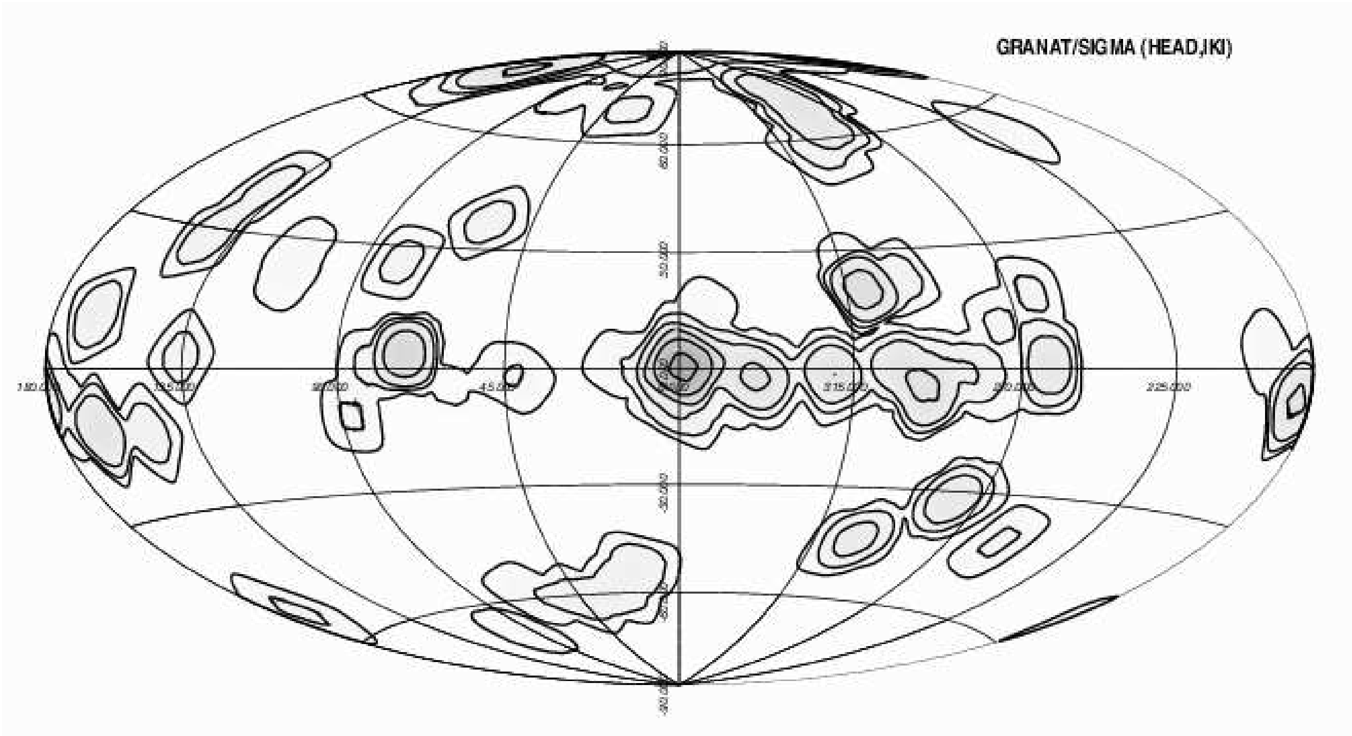

Fig. 1. Exposure map of observations of SIGMA telescope during period 1990-1998. Countours denote region where exposure time is larger than 10,100, 315 ksec, 1.0, 3.16 and 8 Msec.

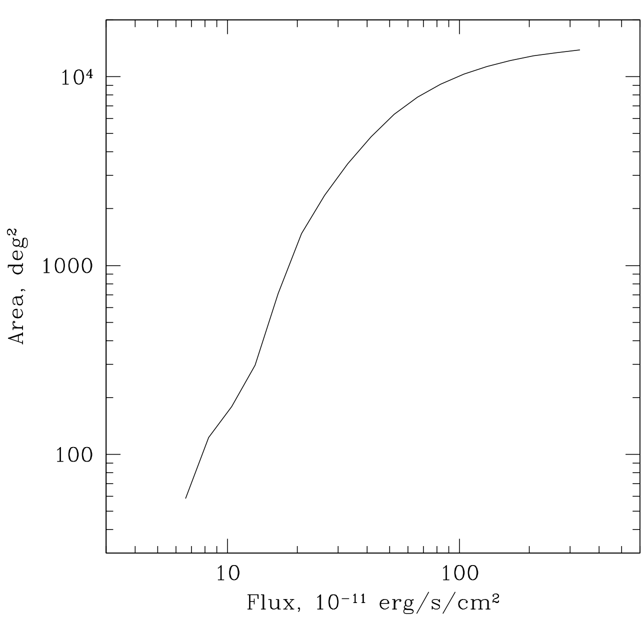

Fig. 2. Dependence of the solid angle of the sky covered with some sensitivity on the value of this sensityivity (5σ).

hours. Total exposure time of all observations (corrected for deadtime fraction) is around 30 million sec. Of this 9 million of sec was spent to observe the Galactic Center region. Map of effective exposure (corrected for deadtime fraction and vignetting – dependence of effective exposure on distance from the center of the field of view) of all performed observations is presented in Fig.1. Contours on Fig.1 denote regions which have exposure times more than 10, 100, 316 ksec, 1.0, 3.16 and 8 Msec.

40-100 keV energy band of the SIGMA telescope is the most sensitive to typical sky X-ray objects. Dependence of sky solid angle on sensitivity achieved by the SIGMA in the energy band 40-100 keV is presented in Fig.2. Contours of sensitivity, achieved by the SIGMA in the Galactic Center region and region of Norma spiral arm tangent are presented in Fig.3. On Figures 2 and 3 sensitivities correspond to 5σ level, i.e. to the level of detection of unknown source. In order to obtain an upper limit on the hard X-ray flux of a source with known position one can use slightly smaller limit, for example 2-3σ. In this case the best value would be $\sim 4-6$ mCrab. For a source with Crab-like spectrum 1mCrab flux value corresponds to energy flux $\sim 10^{-11}$ ergs/s/cm^2 or $\sim 10^{-5}$ phot/s/cm^2, that in turn corresponds to the luminosity $\sim 8\times10^{35}$ ergs/s at the distance of the Galactic Center (8.5 kpc).

During its operation time the SIGMA telescope detected a number of hard X-ray sources: galactic compact objects with neutron stars and black holes, X-ray Novae, active galactic nuclei. In Table 1 we present the list of detected sources. In the last column of the table we present references to works where detailed information about the SIGMA results on these sources can be found.

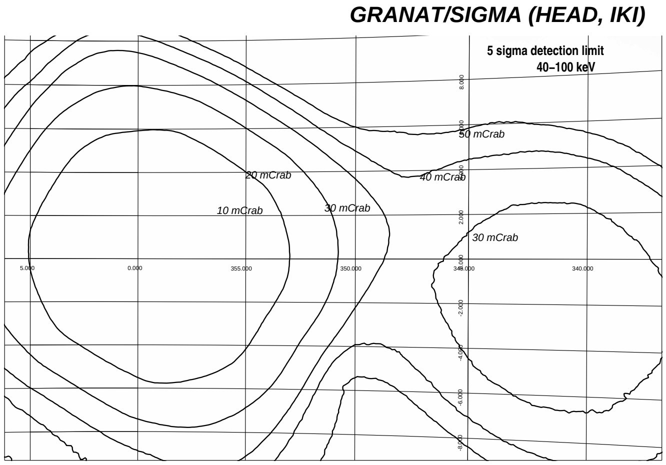

Fig. 3. Countours of sensitivity, achieved by the SIGMA for ne sources detection (5σ) in the region of Galactic Center and Norma arm tangent.

Map of the whole sky, obtained by averaging of all observations is shown in Fig.4. Zoomed image of the Galactic Center region and region of Norma spiral arm tangent is presented in Fig.5. It is worth to note that because we present here only averaged images of regions, some weak and variable or transient sources are not visible on these images (for example KS/GRS 1730-312, GRS 1739-278, KS 1731-260 and so on)

Typical sensitivity of the SIGMA for detection of new sources over approximately one quarter of the sky is $\sim$100 mCrab, that is somewhat worse that the previous all sky survey performed by scanning collimator A4 of HEAO1 observatory (typical sensitivity of this survey in 40-100 keV energy band is $\sim$ 10–15 mCrab, see. Levine et al. 1984). However, very good spatial resolution of the SIGMA allowed it to make a set of interesting discoveries in a very crowded region of the Galactic Center, that was impossible for HEAO1/A4. Sensitivity of the SIGMA in the Galactic Center region is $\sim$8–10 mCrab (5σ), that is comparable with that of HEAO1/A4.

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Table 1.. Table of sources detected by the SIGMA in energy band 40-100 keV

Source	$F_{\mathrm{max},40-100\mathrm{keV}}$, mCrab	Class	Refs
	Galactic sources		
Crab^h	1000	Pulsar	1
Cyg X-1^h	2000	BH	2,3,4
1E1740.4-2942^h	150	BH	4,5,6,7
GRS 1758-258^h	100	BH	5,8,9,10
GRS 1915+105^h	150	BH	11
GX339-4^h	430	BH	12,13
SLX 1735-269	20	NS, Burster	14
KS 1731-260	70	NS, Burster	15
TrA X-1	80	BH?	16
4U1724-30(Terzan 2)	50	NS, Burster	16,17
H1732-304(Terzan 1)	10	NS, Burster	18
GX354-0(4U1728-34)	100	NS, Burster	19
A1742-294	30	NS, Burster	20
4U1705-44	70	NS, Burster	21
4U1608-52	70	NS, Burster	21
4U1700-37	200	NS,HMXB	22,23
OAO 1657-415	100	NS, Accr.Pulsar	24
Vela X-1	200	NS, Accr.Pulsar	25
GX1+4	100	NS, Accr.Pulsar	26,27
PSR 1509-58	17	NS, Pulsar	28
GRS 0834-430	100	NS, Accr.Pulsar	29
GRO J1744-28	120	NS, Accr.Burster-pulsar	30
Sgr A*	<10	SBH	5,31
GRS 1227+025	100		32
	Extragalactic sources		
Cen A	130	AGN	33,34,35
3C273	40	Blasar	34,36
NGC 4151	40	AGN	34,37,38
NGC 4388	10	AGN	39
GRS 1734-292	36	AGN	40
	X-ray Novae		
Nova Musca 91 (GS/GRS 1124-68)	1070	BH	41,42,43
Nova Persei 92 (GRO J0422+32)	2800	BH	44,45,46,47,48
Nova Oph 93 (GRS 1716-249)	1200	BH	49
Nova Vel 93 (GRS 1009-45)	65	BH	50
KS/GRS 1730-312	170	BH	51,52
GRS 1739-278	100	BH	53
GRS 1737-31	115	BH	54
XTE J1755-324	85	BH	55,56

^{h} - source also was detected in 100–200 keV energy band

1- Gilfanov et al. 1994, 2 - Salotti et al. 1992, 3 - Vikhlinin et al. 1994, 4 - Kuznetsov et al. 1997, 5 - Sunyaev et al. 1991a, 6 - Bouchet et al. 1991, 7 - Sunyaev et al. 1991b, 8 - Laurent et al. 1993a, 9 - Gilfanov et al. 1993, 10 - Kuznetsov et al. 1999, 11 - Finoguenov et al. 1994, 12 - Bouchet et al. 1993, 13 - Trudolyubov et al. 1998, 14 - Goldwurm et al. 1996, 15 - Barret et al. 1993, 16 - Barret et al. 1992, 17 - Barret et al. 1991, 18 - Borrel et al. 1996, 19 - Claret et al. 1994, 20 - Churazov et al. 1995, 21 - Revnivtsev et al. 1997, 22 - Laurent et al. 1992, 23 - Sitdikov et al. 1993, 24 - Mereghetti et al. 1991, 25 - Laurent et al. 1995, 26 - Laurent et al. 1993b, 27 - David et al. 1998, 28 - Laurent et al. 1994, 29 - Denis et al. 1993, 30 - Meji'a et al. 2002, 31 - Goldwurm et al. 1994, 32 - Jourdain et al. 1992a, 33 - Bassani et al. 1993, 34 - Churazov et al. 1994b, 35 - Bond et al. 1996, 36 - Bassani et al. 1992, 37 - Jourdain et al. 1992b, 38 - Finoguenov et al. 1995, 39 - Lebrun et al. 1992, 40 - Churazov et al. 1992, 40 - Gilfanov et al. 1991, 41 - Sunyaev et al. 1992, 42 - Goldwurm et al. 1992, 43 - Claret et al. 1993, 44 - Roques et al. 1994, 45 - Denis et al. 1994, 46 - Vikhlinin et al. 1995, 47 - Finoguenov et al. 1996, 48 - Revnivtsev et al. 1998, 49 - Goldoni et al. 1998, 50 - Trudolyubov et al. 1996, 51 - Vargas et al. 1996, 52 - Vargas et al. 1997, 53 - Trudolyubov et al. 1999, 54 - Revnivtsev et al. 1999, 55 - Goldoni et al. 1999

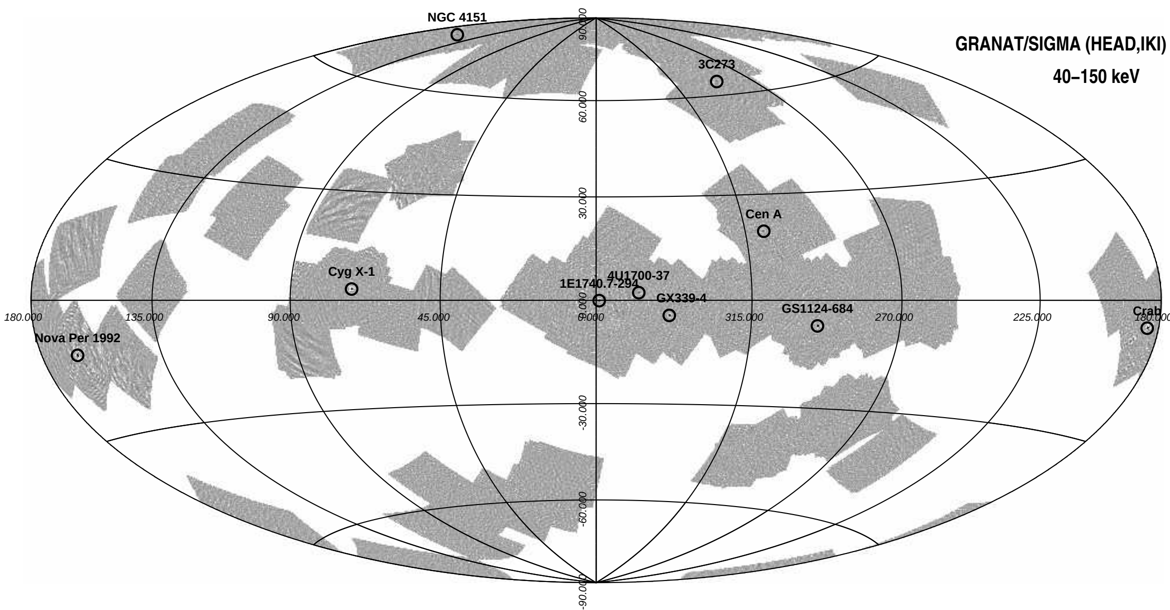

Fig. 4. Map of the whole sky averaged over all observations. Only brightest sources are marked.

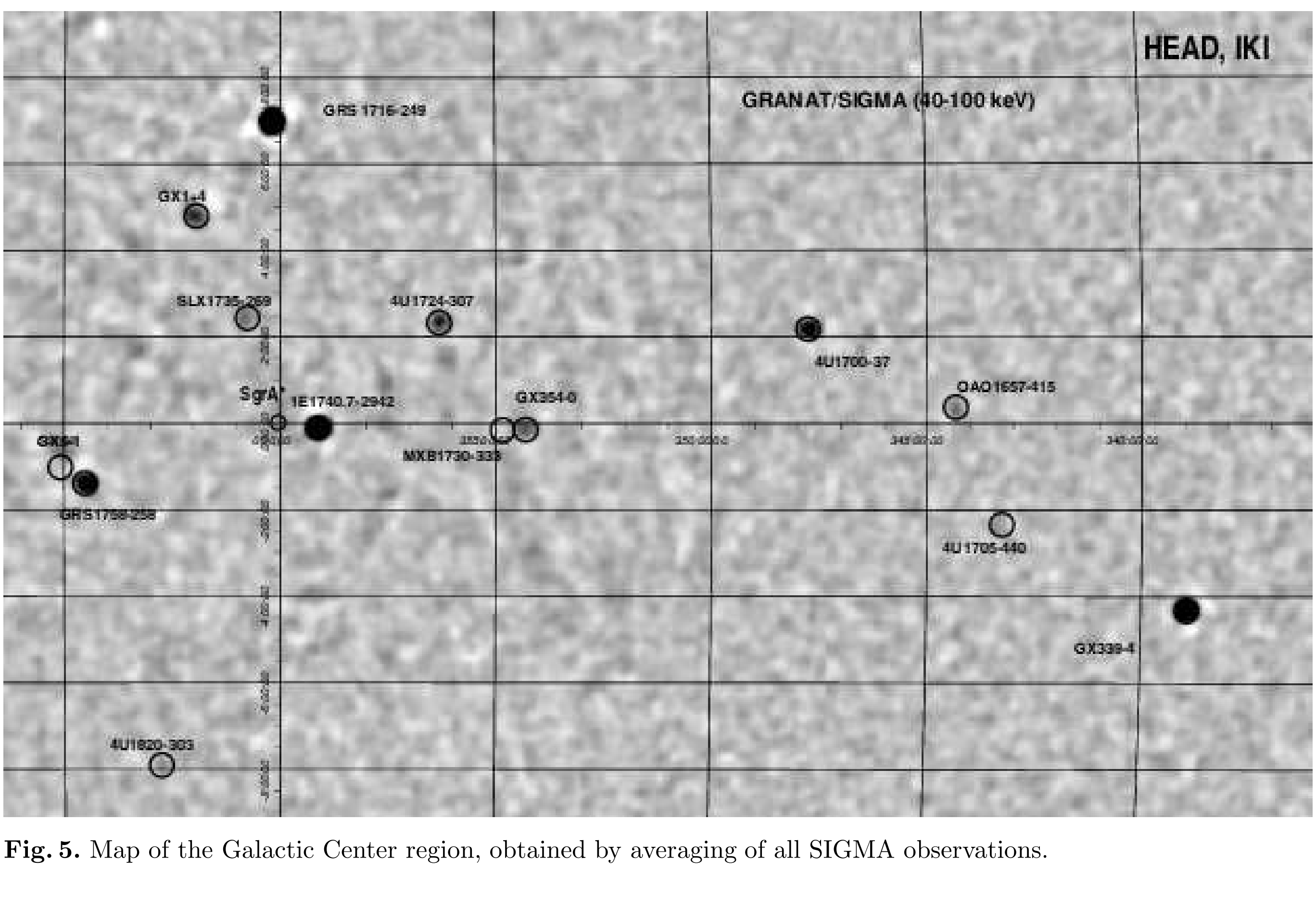

Fig. 5. Map of the Galactic Center region, obtained by averaging of all SIGMA observations.